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Sustainability of additive manufacturing: An overview on its energy demand and environmental impact

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ABSTRACT

Additive Manufacturing (AM) has been rapidly developing over the last decade. It shows great potential in reducing the need for energy- and resource-intensive manufacturing processes, which in turn reduces the amount of material required in the supply chain, and enables more environmentally benign practices. However, the question of how to realize these potential benefits has received little attention. This paper aims to provide an overview of the Sustainability of Additive Manufacturing (SAM). The context of the SAM is introduced, with a focus on energy and environmental impacts. Resource consumption is identified as the most important aspect. Examination from a life cycle perspective is also presented, with explicit discussions on opportunities to reduce energy and material consumption through design, material preparation, manufacturing, usage, and end-of-life treatment. Statistical data analysis provides an overview of impact forecasts, highlighting the importance of and need for thorough research on sustainability. The eco-design concept enabled by AM is identified as the most promising and effective technology, further extending and completing its design capability. This also determines the opportunities for energy and environmental optimization in subsequent processes. Most existing research is in process- and system-specific modeling, and few AM processes and systems have been studied, with generally premature conclusions. General models for each type of AM process are still necessary. Lastly, five research priorities are suggested: improve systematic data integration and management, correlate energy and quality, develop intelligent machinery, focus on material preparation and recycling, and discover innovative applications using AM.

1. Introduction

Industrial metabolism, defined as the transformation of matter, energy, and labor into goods, services, waste, and ambient emissions, has generated high levels of value, while accounting for increasing environmental impact [1]. The industrial sector represented 22% of global energy consumption in 2012 [2] and is considered a major sector where transformative changes are needed toward sustainability [3]. Additive Manufacturing (AM), also known as 3D printing or rapid manufacturing, has been rapidly developing recently. This is mainly due to the technical advantages offered by the construction of highly complex and customized products that were previously impossible or impractical using traditional methods [4,5]. AM processes have proven to be compatible with actual production, beyond prototyping [6]. New component design with complex geometries and structures and heterogeneous compositions can be fabricated with relative ease using AM technologies. The supply chain will be compressed and considerably more flexible under the future decentralization of production subject to AM machines, and production may become less capital-intensive, more autonomous, and achievable in shorter production cycles [7,8]. Claimed as a green technology [9,10], AM holds great potential in improving materials efficiency, reducing life cycle impacts, and enabling greater engineering functionality compared to conventional methods, including less requirement for special tooling in part fabrication, rapid tooling production, and reduced material waste. Consequently, time and cost can be potentially reduced for individualized and small-volume parts manufacturing [11]. However, existing research asserts that realizing such potentials remains beyond reach. As such, this study addressed the issue of sustainability in AM, focusing on its environmental impact, providing the latest developments on the

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Sustainability of Additive Manufacturing (SAM). Further, this study motivates research towards more environmentally benign AM technology. The following abbreviations are used in this paper.-ABSAcrylonitrile Butadiene StyreneAMAdditive ManufacturingCMConventional ManufacturingCNCComputer Numerical ControlCO2PE!Cooperative Effort on Process Emissions in ManufacturingEBMElectron Beam MeltingEUEuropean UnionFDMFused Deposition ModelingGHGGreenhouse GasLCALife Cycle AssessmentNC-Numerical ControlPETPoly Ethylene TerephthalatePLAPoly Lactic AcidSAMSustainability of Additive ManufacturingSECSpecific Energy ConsumptionSLAStereo Lithography ApparatusSLSSelective Laser SinteringSMSubtractive ManufacturingSTLStereolithographyUFPUltra-Fine Particle

The remainder of this paper is organized into five sections. Section 2 presents the background and status of the AM industry, demonstrating the need to conduct thorough research on its energy and environmental impacts. Section 3 provides an overview of SAM and introduces life cycle methodology to study its environmental aspect. Section 4 is a review of existing research on four key topics: high-level statistics, eco-design, process- and system-specific modeling, and multi-criteria optimization. Research gaps and priorities in improving energy and environmental performance are summarized in Section 5. Finally, Section 6 presents some concluding remarks.

2. The AM industry

AM processes were formally standardized in seven categories [12]. More specifically, 18 different technologies, divided by the physical state of the printed matter as well as the application method, were described [13]. For each technology, a manufacturer may have multiple models in terms of the build envelope, fabrication speed, materials selection, accuracy/resolution, and layer thickness [11]. AM has been mainly used for rapid prototyping in the aerospace, automotive, and machine tool production sectors, as well as in medical and dental care, and approximately 150 companies operate in these markets [14]. Even though the rapid prototyping market is expected to exceed $20.2 billion by 2020 [15], rapid manufacturing is anticipated to be an even more promising market.

Since 2014, Gartner has reported annually a detailed hype cycle for different technologies in the AM industry, and Fig. 1 illustrates the different evolving speeds of AM technologies [16]. The AM industry has grown from $295 million to $5.1 billion over the past 25 years, with a compound annual revenue growth rate for all AM products and services worldwide of 25.4% [17]. This growth occurred in all segments, including both the entry-level desktop 3D printer and industrial metal AM systems. A more aggressive forecast is $230-550 billion by 2025 [18], where the primary markets identified are $100-300 billion in consumer products and $100-200 billion in direct part manufacturing of medical and aerospace components.

AM is anticipated to be incorporated and employed in industrial production to significantly improve the flexibility and efficiency in mass personalization of complex parts. It can complete the manufacturing capability profile via incorporation with subtractive manufacturing (SM) processes, for instance, in emerging hybrid manufacturing [19,20]. Moreover, it has been found that the economy-of-scale model in conventional manufacturing (CM) is not relevant in AM, leading to a model named economy-of-one [21]. Implementing strategies have also been suggested to assist companies in introducing AM into businesses [22].

In the foreseeable future, the sustainable growth of the AM industry is vital. Research on SAM, particularly, to quantify and minimize the environmental impacts of AM, must be performed before the industry develops further [23]. In a review on metal AM processes and powder metallurgy conducted by Frazier [24], the potential of AM in reducing cost, energy, and resource consumption was recognized, but more work is required. Additionally, existing research in this arena lacks consistency and continuity, partially due to the variety of AM processes, but more importantly, the absence of a strategic plan. This paper, therefore, aims to provide an overview of research on the SAM. A focused review on the energy and environmental impact of AM is presented, and collaborative research efforts towards the development of more environmentally benign AM technologies is motivated.

3. Sustainability of additive manufacturing

The issue of sustainability was recognized in the manufacturing

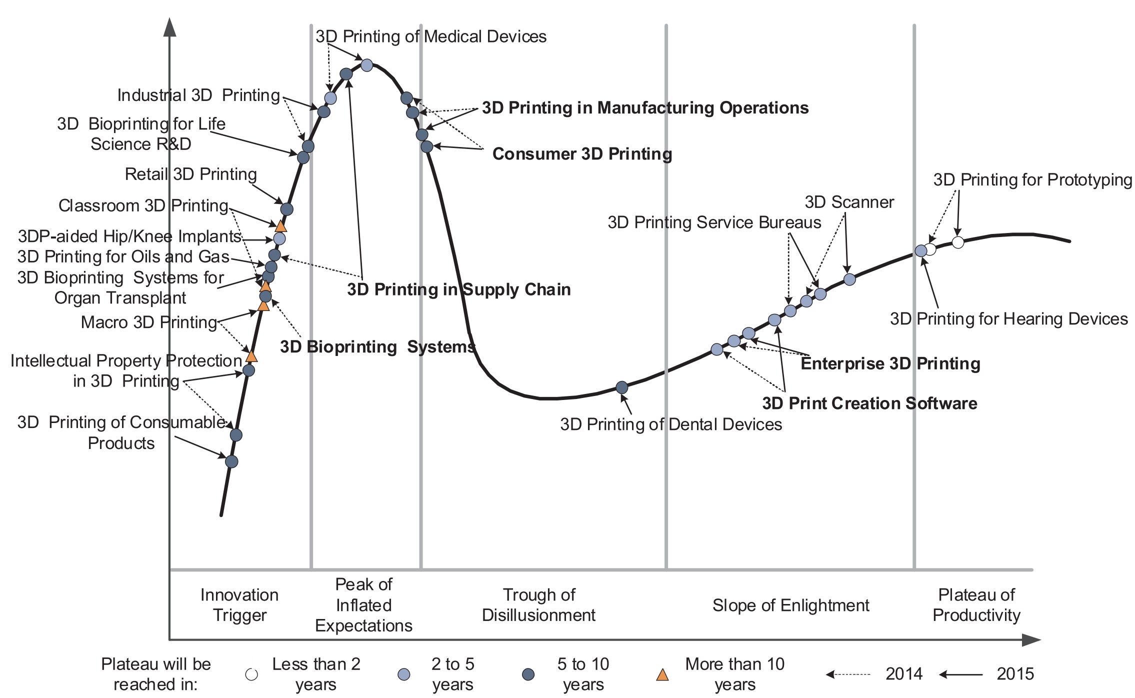

Fig. 1. Evolution of AM technologies [based on Gartner report [16,119].